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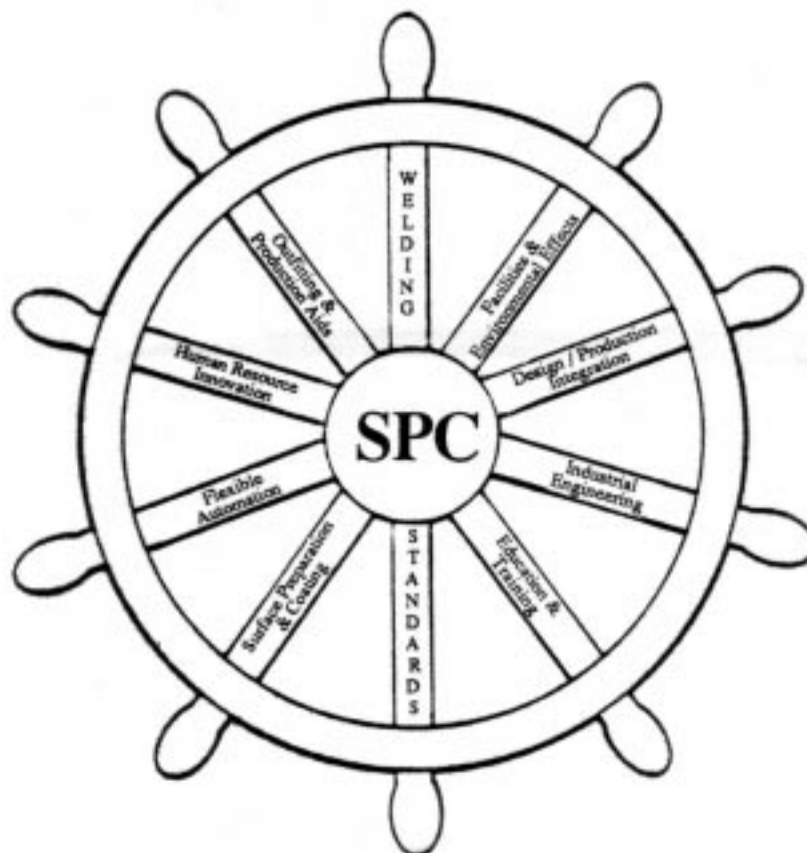
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Standardization in Ship Structural Design

1A-1

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Abstract

This paper presents two methodologies for the automatic structural design of the midship section of a ship based on the American Bureau of Shipping (ABS) classification rules. The first methodology has as an objective the minimization of the steel required to build the structure of the ship and is based on the solution of a non-linear minimization problem subject to bounds on the variables, linear and non-linear constraints. The second methodology uses a heuristic algorithm based on the use of standard structural shapes to reduce the material cost required for the construction of the ship, while at the same time avoiding a significant penalty in the increase of the structural weight of the ship. Cost data from an actual steel mill are obtained and alternative structural designs for two oil carriers are evaluated according to their material cost and weight differentials. A net present value cost model is then developed to assess the cost advantages of standardization in structural design.

1. Introduction

It is standard practice among ship designers during the preliminary design of a new vessel to use an approach to minimize the structural weight of the ship, since smaller weight results in smaller cost and higher carrying capacity. However, a minimum weight design requires many variations in the properties of the plates and stiffeners composing the ship structure resulting in an increase in the manufacturing cost of the ship. This increase is caused from the use of non-standard plates and stiffener sections, which need to be custom-made in small batches at a higher unit cost.

In this paper we contrast two methodologies for the structural design of a ship. The first methodology minimizes the structural weight of the ship while the second methodology minimizes the cost of the structure of the ship through the use of standardization. To assess the advantages and disadvantages of the two methodologies, a cost model is developed to compare structural costs of new ship structural designs. The main variables to compare are the increased cost of a non-standard ship structure and the reduction in carrying capacity of a heavier standard ship structure. Actual cost data for structural sections from a U.S. steel mill are used to perform these comparisons. The parallel midbody section of a tanker is the basis of our studies on structural design and cost estimation with the two methodologies. The number of variations on the

structural properties of the ship structure (plate thickness, stiffener spacing and size) is also varied to assess the effects of using fewer structural shape variations to design the structure of the ship. The American Bureau of Shipping Rules for Building and Classifying Vessels (ABS Rules) are used as a basis for the design of a structurally acceptable ship midship section. A more detailed presentation of the material in this paper can be found in [Kriezis 90].

2. Structural Design Model

It is standard practice among ship designers to design the structure of a ship using classification rules to select the scantlings of the hull structural members. This approach is used also in this work to provide a common framework to compare the two methodologies of minimum weight and minimum cost structural design. The ABS Rules applying to tankers intended for unrestricted ocean service were used [ABS 83].

Since our analysis is based on the structural design of the parallel midbody section of a ship, the design variables considered are limited to the midship hull-girder section modulus and stiffness, shell and deck plating sizes, longitudinal bulkhead sizes, longitudinal stiffener sizes and spacing, and transverse bulkhead spacing. To simplify the analysis the ship is assumed to be designed as a single bottom ship with longitudinal framing with a maximum of two longitudinal watertight bulkheads. There are several types of stiffeners used in ship construction, such as tee, flatbar, offset bulb plates, angles, and channels [Taylor 85]. To reduce the number of unknown elements, we selected to use only tee stiffeners for all the longitudinal elements in the structural design of our tankers. It should be mentioned that tees have a higher cost as compared to other types of stiffeners. Our selection was based more on the information available about different types of stiffeners, than on their cost. The sizing of the transverse bulkheads is not included in our analysis in order to reduce the number of variables in the two structural design methodologies described below.

An idealization of the midship section as used in our algorithms is shown in figure 2-1. The midship section of the ship is split into zones, each of which has its own stiffening arrangement and shell plating. The bottom shell and the deck are each one zone, while the side shell and the longitudinal bulkhead can be split in a number of zones, to

account for the different loading requirements at the different depths in the side of the hull and the oil tanks. For each zone the unknown variables that we want to determine, are the plate thickness (t_p), the stiffener spacing (s), the stiffener web thickness (t_w) and width (w_w) and the stiffener flange thickness (t_f) and width (w_f). These are shown in figure 2-2.

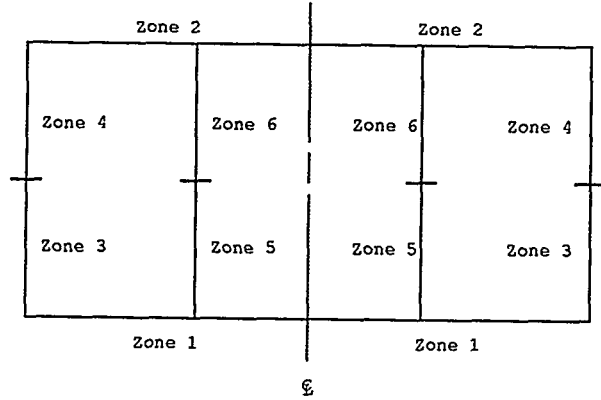


Figure 2-1: Midship Section Idealization

The structural strength of a ship is expressed as minimum requirements for 1) the midship hull-girder section modulus and moment of inertia, 2) the section modulus of longitudinal or bulkhead stiffeners and 3) the thickness of the various plates of the shell, deck or bulkheads of the ship. The empirical formulas specifying these minimum requirements depend on the gross characteristics of the ship and the strength of the material used [ABS 83]. In the calculation of the section modulus of a certain design, the following items are included, under the assumption that they are continuous and effectively developed:

- Deck and shell plating
- Plating and longitudinal stiffeners of longitudinal bulkheads
- All longitudinals of deck, sides and bottom

Shear stresses which may be important for certain classes of vessels, are not accounted for in this study. The net sectional area of the above items is used in the hull-girder section modulus calculation. The effect of isolated openings on these elements is ignored assuming they are small in size.

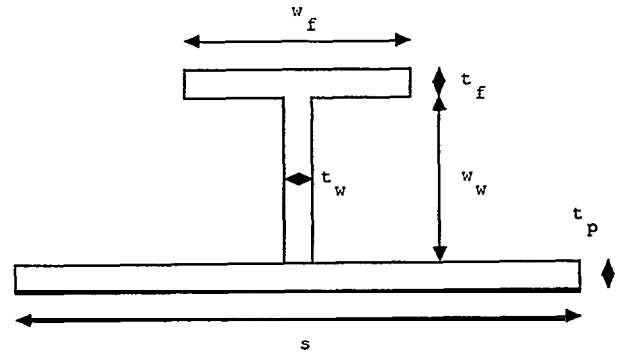


Figure 2-2: Zone Variables

3. Minimum Weight Structural Design

3.1. Problem Formulation

The first methodology used for structural design is based on minimization of the structural weight of the ship structure subject to the constraints imposed by the classification society rules. This problem is formulated as a non-linear programming problem. To simplify the formulation as was stated before, we are concerned with the longitudinal strength elements of the midship section of a tankship and our objective is to size these elements to obtain a midship section that requires a minimum quantity of steel material.

The problem is formulated as a minimization of the midship sectional area of the ship:

$$\text{Minimize } \sum A_i \quad (1)$$

where A_i is the sectional area of zone i and contains plate area and tee stiffener area, subject to fixed bounds on the variables and linear and nonlinear inequality constraints imposed by the strength requirements of the Classification society rules.

The first non-linear constraint is as follows:

$$SM_{midship} - SM_{required} \geq 0 \quad (2)$$

where $SM_{midship}$ is the section modulus of the actual midship section of the ship calculated in the current solution vector, while $SM_{required}$ is the required section modulus for the midship section of the ship from the ABS Rules (accounting for the primary loads in the ship structure) [ABS 83]. The section modulus of the midship section of the ship is determined by taking into account all plates and longitudinal stiffeners in the midship section of the ship.

The second set of nonlinear constraints is as follows:

$$SM_i - SM_{i,required} \geq 0 \quad (3)$$

where SM_i is the section modulus of a stiffener in structural zone i as calculated from the local plate thickness, stiffener spacing, web thickness and width, and flange thickness and width, and $SM_{i,required}$ is the required section modulus for zone i as specified in the ABS Rules

(accounting for secondary loads in the ship structure) [ABS 83]. If there are n zones specified in the ship, there are $n+1$ non-linear constraints to satisfy.

In addition, we specify fixed bounds to the variables, to restrict them to reasonable values. From the classification rules there are requirements for a minimum plate thickness for all shell plates to account for local structural loads. These provide the fixed lower bounds for all plate thicknesses, i.e.

$$t_{p,i} > t_{p,i,required} \quad (4)$$

The remaining bounds were determined from empirical data about sizes of plates and stiffeners manufactured in steel mills [American 80]. The values used are as follows:

$$\begin{aligned} t_{p,i} &< 3.2 \text{ cm}, & 0.8 \text{ cm} < t_{w,i}, t_{f,i} < 4 \text{ cm}, \\ 15 \text{ cm} &< W_{w,ip} < W_{f,i} < 90 \text{ cm and} \\ 0.75 \text{ m} &< S_1 < 1.1 \text{ m} \end{aligned} \quad (5)$$

where i indicates the corresponding zone.

A number of linear constraints relating the size of the stiffener web to the size of the stiffener flange were also included in the formulation, to resolve some initial problems with obtaining a manufacturable and structurally adequate solution. A minimization approach on the size of a stiffener tends to increase the size of the stiffener flange, (decreasing the size of the stiffener web) since the flange contributes more to the section modulus of the stiffener and might lead to a stiffener with torsion problems. As a result we require that:

$$w_{w,i} > w_{f,i} \quad \text{and} \quad t_{w,i} > 0.6 t_{f,i} \quad (6)$$

These approximate values were obtained from stiffener data from the steel construction manual [American 80]. In addition, to avoid buckling of a stiffener web, the web width to web thickness ratio is limited by:

$$w_{w,i} < 60 t_{w,i} \quad (7)$$

An additional constraint which could be imposed is the limit in the transitions allowed between plate thicknesses in neighboring structural zones. Equations 1-7 complete the formulation of the non-linear minimization problem. If there are n structural zones, there are $6n$ variables to determine, $n+1$ non-linear constraints and $3n$ linear constraints to satisfy.

3.2. Solution Method

There is a substantial body of literature dealing with the solution of non-linear constrained optimization problems, and there are several techniques that have been proposed for such problems [Gill 74]. Since the problem is non-linear all algorithms proposed for its solution are iterative in nature and as a result require an initial approximation to the solution. Then information from the first and second derivatives of the objective function and the first derivative of the constraint functions is used to march from the initial approximation to the problem solution. A limitation of non-linear minimization problems is that there is no way to guarantee that the solution obtained represents a global minimum of the minimizing function. As a result different initial approximations may result in different local minimum solutions, or no solutions at all.

For our problem, we selected to use a sequential quadratic programming (SQP) algorithm in which the search direction is the solution of a quadratic programming problem. An explanation of this method can be found in [Gill 74, Gill 81, Kriezis 90, Murray 76]. This algorithm, as implemented in a Numerical Algorithms Group (NAG) routine [NAG 88], is used to solve the minimum structural weight problem formulated above.

4. Structural Design For Standardization

It is desirable during the preliminary structural design of a new ship to try to minimize its structural weight since smaller weight implies less steel required and as a result less material cost. A technique similar to the one presented in the previous section can be used towards such a goal. However, a technique that tries to minimize structural weight for each ship design requires the use of non-standard structural shapes, such as built up plates and stiffener sections. These need to be custom-made in small batches for each particular ship. This results in higher procurement unit costs for these elements, and the cost advantage of a smaller weight design is quickly eliminated.

Our objective was to develop a technique to design the structure of a ship using only standard sizes for plates and stiffener sections, while at the same time attempting to minimize the resulting structure weight from the use of such elements. We have developed a heuristic algorithm, that uses a database of plate sizes and stiffener sections that represent standard products from steel mills and incrementally builds a midship structure by selecting larger plates and stiffener sections, until the section modulus of the midship steel structure and the section modulus of the local stiffener structure in each zone satisfy the ABS Rules. This algorithm is presented in detail in the following section.

4.1. Heuristic Algorithm for Minimum Cost Standardized Design

The first element of the algorithm is the establishment of the database of standard structural shapes. In order to accomplish this the manual of the American Institute of Steel Construction [American 80] was used. It provides characteristics for structural sections which are standard products of U.S. steel mills, as well as information on the standard plate sizes. For our analysis, we used structural tees that are cut from W shapes [American 80]. One source of the tee sections used are obtained by cutting structural I-beams in half, a standard practice among steel mills (half I-beam). The other source of the tee sections used are obtained by removing one of the flanges of a structural I-beam (double web tee). These tees are also standard products, although they cost slightly more than half I-beams, see figures 5-2 and 5-3.

The standard plates available in our database range between 1/2 inch to 1 inch thickness every 1/16 of an inch and between 1 inch to 1.5 inch thickness every 1/8 of an inch. One decision made early in our implementation to reduce the unknown variables for the cost minimization was to make the spacing between the stiffeners in a structural zone an input to the algorithm. This represents another aspect of standardization in the spacing of

elements. Each of the standard plate thicknesses in the database was associated with a number of standard stiffener spacings (0.75 m, 0.8 m, 0.9 m, 1.0 m) and the resulting structural plate area between stiffeners was computed.

An additional step in the preparation of the database for our algorithm was to sort the elements of the database according to different criteria in increasing order. The two criteria used were structural element area and structural element cost. For plate thickness the result from sorting is identical for both criteria, since cost is proportional to area. For the tee stiffeners the result from sorting is not identical from both criteria, since we have the two types of stiffeners mentioned above (half I-beam, double web tee) with different unit costs per unit area. However, within each tee category cost is still proportional to unit area and the sorting results are identical.

The approach used in our algorithm follows very closely the manual structural procedure which a ship designer uses. To begin with, we look locally in each structural zone and determine the appropriate plate thickness and tee from the sorted database to satisfy the local stiffener section modulus requirements from the rules, and then minimize the area or the cost of the zone sections. The heuristic procedure for this local minimization has the following steps (the algorithm is presented for the databases which are sorted by area):

1. Determine the minimum plate thickness and section modulus required from the rules for the particular zone, t_{res} , SM_{req} .
2. Find the minimum plate thickness t_i in the sorted plate database, which is $t_i \geq t_{res}$.
3. Find the minimum area tee in the sorted tee database with index j , which with plate t_i and the input spacing s_j creates a stiffener with section modulus $\geq SM_{req}$.
4. Calculate area of stiffener section $A_{s,i} = A_{plate} + A_{tee}$.
5. Once i, j are found iterate:
 - Use next larger plate in the database (increment i), and find a new j index for the minimum area tee satisfying the section modulus requirement as above. Compute the new area $A'_{s,i}$.
 - If $A'_{s,i} < A_{s,i}$, use the new i, j indices and repeat the iteration
 - else, the minimum area for the stiffener in this zone has been found

This algorithm does not require checking of all plates in the database, since the condition $A'_{s,i} < A_{s,i}$ is not satisfied for the thicker plates which contribute more area in the stiffener in relation to their contribution to the local section modulus. This algorithm provides a good estimate of the minimum area stiffener for each zone, and our experience is that it results in a balanced tee stiffened plate combination.

Once the initial selection for each zone is performed with the above procedure, the midship section modulus of the resulting structure is computed and is compared to the required midship section modulus from the ABS Rules. If it satisfies the requirement, the current characteristics represent our solution. If it does not satisfy the requirement, the sizes of the structural elements need to be increased and new plates and tees need to be selected. The procedure in this case is the following: If there are n structural zones, we have n plate thicknesses and n different types of tees to select from the database. The current solution is represented as $2n$ indices representing elements in the plate and tee databases.

For each element in the solution vector, we select the next larger element in the database (or jump over a few elements in the case of tees) and we compute the relative percentage increase of the midship structure section modulus with the new index versus the old index in relation to the increase in the midship sectional area or the increase in structural cost. Specifically we compute

$$\%i = SM_{new}/SM_{previous} * A_{i,previous}/A_{i,new}$$

where i denotes the element of the solution vector, and A_i denotes the midship sectional area or the midship cost. The relative percentage changes ($\%$) for all elements are compared and the one contributing the larger increase is selected to update the solution vector. The updated solution is examined for satisfaction of the section modulus requirement amidships, and if the test fails the above process is repeated until the section modulus requirement is satisfied. In this way a good approximation to the minimum weight or cost standard design is obtained.

Two elements should be noted in the above algorithm. Since the plates at the top and bottom of the ship shell sometimes contribute the largest increase in sectional properties repeatedly (largest δ_i resulting in a ship structure with thick plates, the user is given the freedom to limit the maximum thickness of the ship plates. In this case the plates which reach the thickness requirement during the incremental process described above are not considered in the continuation of this process. The tee database contains stiffeners of varying characteristics and in many cases neighboring elements with approximately the same sectional area contribute differently to the overall midship section modulus. As a result, the incremental process at one of these elements might stop because of the inefficiency of the neighboring element. In these situations the algorithm allows the incremental process to jump over some of the inefficient stiffeners.

The above algorithm represents an excellent methodology for automated structural design of ship midship sections based on standard plates and stiffeners. It uses heuristic arguments to avoid the combinatorial explosion of checking all possible combinations of structural elements and plate sizes to minimize the area or the cost and as a result is very fast. It does not guarantee a minimum but approximates this minimum by trying to simulate the performance of a minimization algorithm. A minimization algorithm moves in the direction of the gradient (maximum change) of the objective function and, in our algorithm, we select to increment the element which increases the midship section modulus the most relative to the increase in the sectional area or the cost.

5. Costs Modeling

One of the objectives of our work was to determine the relative advantages and disadvantages of applying the structural design methodologies presented in the previous sections. In this respect, we want to make a relative cost comparison between designs from the two methodologies. Structural design based on the minimum weight methodology presented in section 3 results in a lower weight midship section made of non-standard parts which have high material cost. Structural design based on the standardization methodology results in a heavier midship section made of parts with low material cost. The savings in material cost in this case should be examined in relation to the potential loss in carrying capacity of the heavier vessel over its lifetime.

Material cost data for plates and stiffeners in standard or non-standard production were obtained from an actual steel mill [Bethlehem 89]. These data are presented in figures 5-1 to 5-3. Figure 5-1 presents the price in US dollars of a metric ton of plating as a function of plate thickness for standard and non-standard plate thicknesses of mild and high tensile strength (HTS) steel. As can be seen in this figure, non-standard plates cost about 20% more than standard plates of comparable thickness. Figure 5-2 presents the price per metric ton of tee stiffeners made from mild steel as a function of the tee sectional area, while figure 5-3 presents similar data for high tensile strength tee stiffeners. In these figures, data for normal tees, tees that are cut from an I-beam (in half), tees that are obtained from an I-beam by removing one flange (double web), and non-standard size tees are shown. As can be seen in these figures, non-standard structural tees cost about 50% more than equivalent tees from the other standard categories. Data from these figures were used to evaluate the material cost of different bulk oil carrier midship structural designs. Linear extrapolation was used for elements outside the available range of plate thicknesses and tee sectional areas of figures 5-1 to 5-3.

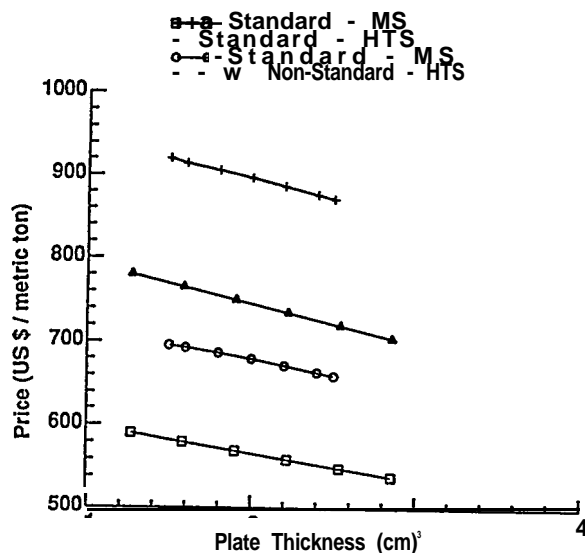


Figure 5-1: Plate Cost Data - All U.S. Prices for May 1989

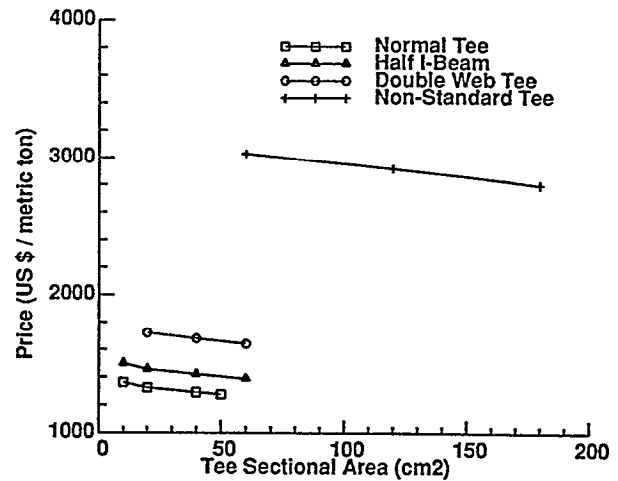


Figure 5-2: Mild Steel Tee Cost Data - All U.S. Prices for May 1989

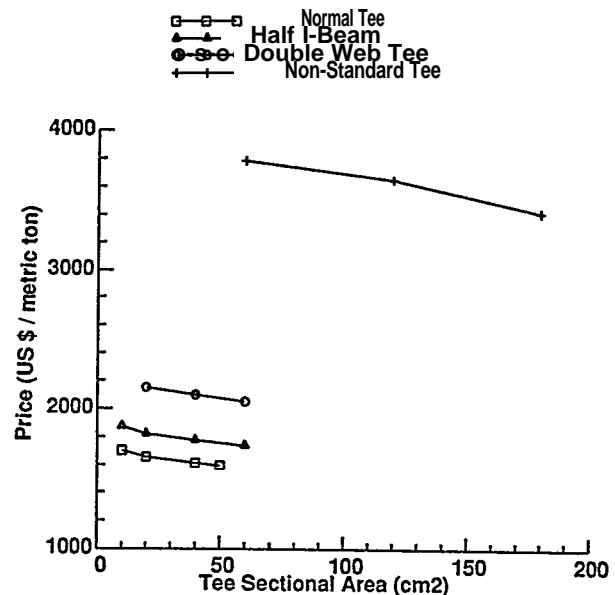


Figure 5-3: HTS Steel Tee Cost Data - All U.S. Prices for May 1989

Once the material cost for the different midship sections resulting from the two methodologies is computed, an approximate cost model is used to evaluate the net present value (NPV) resulting from the use of standardization. This model assumes that the only value differences between the minimum weight design and the standard design are due to the different material costs, and the loss of carrying capacity over the life of the ship of the heavier design (standard design). Accordingly

$$\text{NPV standard.} = \text{AMaterial Cost} - \text{PVcarr, capac.} \quad (8)$$

where

$$\Delta M.C. = L (C_{mw} - C_{st})$$

$$PV_{c.c.} = \sum_{i=1}^N \frac{\eta \Delta Q n_i R}{(1+r)^i}, \text{ and}$$

$$\Delta Q = LP (A_{st} - A_w)$$

with

C_{mw} , C_{st} = material cost per unit length of minimum weight and standard design,

L = ship length,

N = life of ship,

n_i = number of trips per year at full load capacity,

R = freight rate per cargo ton assumed constant for the life of the ship,

ΔQ = loss in carrying capacity per trip,

η an efficiency factor to account for the costs of additional cargo capacity,

A_{st} , A_{mw} = midship sectional area of standard and minimum weight design,

$p = 7.85 \text{ mton/m}^3$, steel density and

r = rate of return adjusted for inflation.

Our design analysis also predicts the length of stiffener welding required for each of the designs. If this is different for the two designs due to the different stiffener spacing in the various ship zones, the cost of additional welding required can be also added in the material costs in equation 8 according to

$$\Delta C_{\text{welding}} = L R_w (L_{w,mw} - L_{w,st})$$

where

R_w = the cost in material and labor of welding one meter of stiffener and

$L_{w,mw}$, $L_{w,st}$ the length of tee fillet welding required per m of midship section for the minimum weight and standard designs respectively.

The above model provides a reasonable estimate of the relative cost advantages and disadvantages of designing a particular ship for minimum weight versus designing this ship for standardization.

6. Applications

6.1. Procedure & Assumptions

This section presents two example applications of the structural design methodologies presented above. The material cost of different designs is compared and the advantages of standardization are assessed. The procedure followed in the analysis of each of the two examples is given below: 1) the midship section of the ship is split in the minimum of four structural zones (bottom shell, deck shell, side shell, longitudinal bulkhead) and standard designs for various stiffener spacings are determined using the heuristic algorithm of Section 4; 2) the standard designs are then used as initial approximations to solve the minimum weight design problem by solving the non-linear programming problem outlined in Section 3; 3) the number of structural zones is then increased by splitting the **zones** in the side shell and the longitudinal bulkhead and new

standard designs and minimum weight designs are produced. The resulting designs are then compared and their material costs contrasted

Some preliminary information about our analysis is provided below. The database of tee stiffeners used in the standardization analysis contained 116 different tees, half of which were tees cut from I-beams (half tees) and the other half were I-beams with one flange removed (double web tees). The spacing of transverse frames assumed in the analysis of both examples was 4 meters. The results from the analysis are presented in tables 6-1 through 6-7. Each of these tables presents the size of the structural elements in each zone, the required and achieved section moduli for the stiffeners and the ship midship section, the midship sectional area, the plate and tee material cost as computed from the methodology of the previous Section, and the required amount of tee fillet welding.

For the net present value calculation to determine the advantages of standardization the following assumptions were used. The base trip was assumed to be 11,000 miles round trip. For such a trip, a tanker moving at 12 to 14 knots requires a minimum of 35 days. Thus, a maximum of 10 trips per year was allowed in the calculation. The average cost of tanker transportation of oil for an 11,000 mile tip in 1982 was approximately \$1.15/barrel or about \$8.5/mton [Rawlinson 83]. This value changes depending on the market conditions and is usually lower for bigger ships. Values of \$10 and \$20/mton were used in our model. The efficiency factor n accounting for the costs of additional carrying capacity was assumed to be 1.0 (no costs). The life of the ship was assumed to be 20 years and the rate of return adjusted for inflation was assumed to be 15%. For the welding costs estimation the material and labor cost of welding one meter of tee stiffener was assumed to be \$5/m weld (10 min at \$15/hr labor, doubled for the material).

6.2. Large Crude Carrier (121,000 mton)

The first application of the two structural design methodologies is performed on a large crude oil carrier (LCC) with approximately 121,000 mton deadweight displacement. This ship is based on a standard Series 60 hull form [Todd 54] and its gross characteristics are given in table 6-1. Mild steel is used throughout the structural design of this vessel.

Length (LBP)	228.6 m (750.0 ft)
Breadth (Mid)	40.8 m (133.9 ft)
Depth (Mid)	20.5 m (67.3 ft)
Draft (Design)	16.3 m (53.5 ft)
Block Coefficient (C_b)	0.8044
Deadweight	121,000 tons

Table 6-1: Large Crude Carrier Gross Characteristics

Tables 6-2 and 6-3 present the design of the standardization algorithm for this ship, when four structural zones are used in the analysis for a stiffener spacing of 1.00

meter and 0.8 meters. Tables 6-4 and 6-5 present minimum weight designs obtained with initial approximations the designs in tables 6-2 and 6-3. Several things can be observed in these tables. The two standard designs have similar midship structural areas and about the same cost. However, the smaller tee spacing design requires **25%** more tee welding. The two minimum weight designs have also similar midship structural area, although the costs in this case vary as one design requires larger stiffeners and smaller plates. It is characteristic of the minimum weight algorithm results that the sizes of the structural elements are adjusted so that the non-linear section modulus constraints are approximately satisfied at their lower bounds. Minimum weight designs also favor larger spacing between the stiffeners (1.1 m spacing is the upper bound of allowed spacing in the minimization algorithm). It should be noted that as the required section modulus for stiffeners depends on the spacing of the stiffeners which is a variable in the minimization algorithm, these values differ for different spacings. Comparing the results in tables 6-2 and 6-4 we see that the minimum weight design saves 10% of the midship structural area of the standard design. This loss is equivalent to a loss of 900 mtons carrying capacity (1% of the 100,000 mton ship capacity). The savings in construction of the standard design has a present value of \$8614 per m of midship section, while the present value of the loss of carrying capacity is \$2555 per m of midship section at a freight rate of \$10/mton (\$5110 at a freight rate of \$20/mton). The net benefit of standardization is \$6059 per m of midship section (\$3504 in the other case), which could be equivalent to a maximum of \$1.25 million savings for the whole ship if the savings are assumed to continue along the ship length (\$0.7 million at double the freight rate).

Zone	I	tp (cm)	I	tw (cm)	I	ww (cm)	I	tf (cm)	I	wf (cm)	I	s (m)
Bottom	I	2.38	I	1.40	I	50.19	I	2.22	I	31.34	I	1.00
Deck	I	2.38	I	0.89	I	50.19	I	1.14	I	16.51	I	1.00
Side	1	2.06	I	1.17	I	64.49	I	1.63	I	25.30	I	1.00
Bulkhead	1	1.75	I	1.31	I	57.30	I	2.22	I	23.02	I	1.00
Zone	I	Required SM				I	Achieved SM					
	I	(cm3)				I	(cm3)					
Bottom	I	3316.				I	4489.					
Deck	I	386.				I	1672.					
Side	1	I	2250.				I	4040.				
Bulkhead	1	I	2369.				I	4057.				
Required Midship Section Modulus - 34.21 m3												
Achieved Midship Section Modulus - 34.39 m3												
Midship Steuctural Area - 5.33 m2												
Plate cost - s 16000. per m midship section.												
Tee Cost - s 22342. per m midship section.												
Required tee fillet welding = 327 m per m midship section												

Table 6-2: Standard Design Characteristics
for LCC With Tee Spacing = 1 m and
4 Structural Zones

Zone	I	tp	I	tw	ww	I	if	I	wf	s
	I	(cm)	I	(cm)	(cm)	I	(cm)	I	(cm)	(m)
Bottom	I	2.54	I	1.31	57.30	I	2.22	I	23.02	0.80
Deck	I	2.22	I	0.89	50.19	I	1.14	I	16.51	0.80
Side	1	2.06	I	1.09	57.30	I	1.50	I	1-86	0.80
Bulkhead	1	1.75	I	1.31	32.30	I	2.11	I	25.44	0.80
zone	I	Required SM			Achieved			SM		
	I	(cm3)			(cm3)					
Bottom	I	2653.			4134.					
Deck	I	308.			1647.					
Side	1	1800.			2578.					
Bulkhead	1	1895.			2090.					
Required Midship Section Modulus - 34.21 m3										
Achieved Midship Section Modulus - 34.49 m3										
Midship Structural Area - 5.42 m2										
Plate cost - \$ 15995. per m midship section										
Tee cost - \$ 23088. per m midship section.										
Required tee fillet welding - 409 m per midship section										

Table 6-3: Standard Design Characteristics
for LCC With Tee Spacing = 0.8 m and 4
Structural Zones

Zone	I	tp	I	tw	I	W	I	tf	I	wf	I	s	
	I	(cm)	I	(cm)	I	(cm)	I	(cm)	I	(cm)	I	(m)	
Bottom	I	2.35	I	0.91	I	51.85	I	1.52	I	33.42	I	1.02	
Deck	I	2.87	I	0.80	I	26.52	I	1.33	I	17.84	I	1.10	
Side	1	2.05	I	0.84	I	50.18	I	1.39	I	25.92	I	1.10	
Bulkhead	1	1.68	I	0.85	I	50.75	I	1.41	I	27.36	I	1.10	
zone	I	Required SM				Achieved SM							
	I	(cm3)				(cm3)							
Bottom	I	3388.				3388.							
Deck	I	424.				859.							
Side	1	I	2475.				I						2470.
Bulkhead	1	I	2606.				I						2601.
Required Midship Section modulus - 34.21 m3													
Achieved Midship Section modulus - 34.21 m3													
Midship Structural Area - 4.81 m2													
Plate cost - \$ 19659. per m midship section													
Tee cost - \$ 27417. per m midship section													
Required tee fillet welding - 303 m per m midship section													

Table 6-4: First Minimum Weight Design Characteristics
for LCC With 4 Structural Zones

Tables 6-6 and 6-7 present a standard design and a minimum weight design, when eight structural zones are used. The minimum weight design is obtained again with the initial approximation being the standard design. Several things can be observed in these tables. The midship structural areas are reduced as compared to the structural results with the four zones, since the loading in the additional zones is smaller. This reduction is small, indicating that the point of diminishing returns is reached fast in allowing more variations in the structural elements of the ship midship section. Comparing the results in tables 6-6 and 6-7 we see that the minimum weight design in this case saves 9% of the midship structural area of the standard design. The savings in construction of the standard design has a present value of \$8326 per m of midship section, while the present value of the loss of carrying capacity is \$2309 per m of midship section at a freight rate of \$10/mton (\$4618 at a freight rate of \$20/mton). The net benefit of standardization is \$6017 per m of midship section (\$3708 in the other case), which is about equivalent to a maximum of \$1.2 million savings for the whole ship if the savings are assumed to continue along the ship length (\$0.75 million at double the freight rate).

zone		tp (cm)	tw (cm)	ww (cm)	tf (cm)	wf (cm)	s (m)
Bottom		2.26	1.14	57.30	1.90	23.01	1.09
Deck		2.33	0.93	50.19	1.17	16.51	0.75
Side	1	2.05	0.95	57.29	1.48	17.88	1.10
Bulkhead	1	1.68	1.40	32.35	2.34	25.48	0.98
zone		I Required (cm3)	SM I	Achisved SM			
Bottom		3623.		3622.			
Deck		289.		1696.			
Side	1	2475.		2415.			
Bulkhead	1	2312.		2312.			
Required Midship Section Modulus - 34.21 m3							
Achieved Midship Section Modulus - 34.11 m3							
Midship Structural Area m 4.91 m2							
Plate cost - \$ 18487. per m midship section							
Tee cost - \$ 35634. per m midship section							
Required tee fillet welding - 342 m per m midship section							

Table 6-5: Second Minimum Weight Design Characteristics for LCC With 4 Structural Zones

zone		tp (cm)	tw (cm)	ww (cm)	tf (cm)	f (cm)	s (m)
Bottom		2.38	1.40	50.19	2.22	31.34	1.00
Deck		2.54	1.31	25.10	2.12	21.22	1.00
Side	1	2.06	1.17	64.49	1.63	25.30	1.00
Side	2	2.06	1.17	32.25	1.63	25.30	1.00
Side	3	2.22	0.89	25.10	1.14	16.51	1.00
Bulkhead	1	1.75	1.31	57.30	2.22	23.02	1.00
Bulkhead	2	1.43	1.17	32.25	1.63	25.30	
Bulkhead	3	1.43	1.09	28.65	1.50	17.88	1.00
zone		Required SH (cm3)	I	Achieved SM			
Bottom		3316.		4489.			
Deck		386.		1428.			
Side		2250.		4040.			
Side	2	1430.		1714.			
Side	3	609.		678.			
Bulkhead	1	2369.		4057.			
Bulkhead	2	1505.		1666.			
Bulkhead	3	641.		1038.			
Required Midship Section modulus - 34.21 m3							
Achieved Midship Section modulus - 34.29 m3							
Midship Structural Area - 5.07 m2							
Plate cost - \$ 15965. per m midship section							
Tee Cost - \$ 18193. per m midship section							
Required tee fillet welding - 327 m per m midship section							

Table 6-6: Standard Design Characteristics for LCC With Tee Spacing = 1 m and 8 Structural Zones

6.3. Very Large Crude Carrier (230,000 mton)

The second application of the two structural design methodologies is performed on a very large crude oil carrier (VLCC) with approximately 230,000 mton deadweight displacement. The principal dimensions of this ship are based on an example of a VLCC in [Taggart 80] and its gross characteristics are given in table 6-8. High tensile strength steel is used throughout the structural design of this vessel. Reference [Taggart 80] also presents a structural design for this ship, which is shown in table 6-1 and figure 6-1 and is compared with our designs.

zone		tp (cm)	tw (cm)	ww (cm)	tf (cm)	wf (cm)	s (m)
Bottom		2.31	1.00	57.79	1.47	30.91	1.10
Deck		3.19	0.80	25.53	1.01	18.08	1.08
Side	1	2.05	0.89	53.64	1.49	21.03	1.10
Side	2	2.05	0.80	48.00	1.20	17.01	1.10
Side	3	2.05	0.80	28.63		16.30	1.10
Bulkhead	1	1.68	0.83	50.06	1.18	33.36	1.10
Bulkhead	2	1.37	0.80	48.00	1.28	18.02	1.10
Bulkhead	3	0.92	0.80	30.02	0.97	16.82	1.10
zone		I Required (cm3)	SM I	Achieved SM			
Bottom		3648.		3644.			
Deck		416.		686.			
Side	1	2475.		2474.			
Side	2	1573.		1573.			
Side	3	670.		670.			
Bulkhead	1	2606.		2601.			
Bulkhead	2	1656.		1655.			
Bulkhead	3	705.		705.			
Required Midship Section Modulus - 34.21 m3							
Achieved Midship Section Modulus - 34.15 m3							
Midship Structural Area - 4.60 m2							
Plate cost - \$ 19366. per m midship section							
Tee cost - \$ 23258. per m midship section							
Required tee fillet welding - 299 m per m midship section							

Table 6-7: Minimum Weight Design Characteristics for LCC With 8 Structural Zones

Length (LBP)	306.2 m (1004.5 ft)
Breadth (Mid)	48.7 m (159.8 ft)
Depth (Mid)	24.5 m (80.6 ft)
Draft (Design)	18.9 m (61.9 ft)
Block Coefficient (Ch)	0.835
Deadweight	230,000 tons

Table 6-8: Very Large Crude Carrier Gross Characteristics

Table 6-9 presents the design of the standardization algorithm for this ship, when four structural zones are used in the analysis for a stiffener spacing of 1 meter. Table 6-10 presents the minimum weight design obtained with initial approximation the design in table 6-9. Comparing the results in tables 6-9 and 6-10 we see that the minimum weight design saves 7.5% of the midship structural area of the standard design. This loss is equivalent to a loss of 1400 mtons carrying capacity (0.7% of the 210,000 mton ship capacity). The savings in construction of the standard design has a present value of \$30,082 per m of midship section, while the present value of the loss of carrying capacity is \$2850 per m of midship section at a freight rate of \$10/mton (\$5700 at a freight rate of \$20/mton). The net benefit of standardization is \$27,232 per m of midship section (\$24,382 in the other case), which could be equivalent to a maximum of \$8 million savings for the whole ship if the savings are assumed to continue along the ship length (\$7.25 million at double the freight rate).

The ship analyzed in this example, has been used in [Taggart 80] to illustrate the application of classification rules in the structural design of ships. As a result [Taggart 80] presents a structural design for this ship, which has been obtained using the ABS rules manually. Figure 6-1 presents the midship section of this ship as designed in

[Taggart 80]. The structure in figure 6-1 has a linear variation in the tee properties of the side shell and the longitudinal bulkheads. In order to compare with our methodology, this design has been approximated with 8 zones and the result is shown in table 6-11. It should be noted, that this design uses flatbar stiffeners for the deck area as can be seen in table 6-11. Tables 6-12, 6-13 and 6-14 present a standard design and two minimum weight designs, when eight structural zones are used. The minimum weight designs are obtained using as initial approximations the standard design and the design in [Taggart 80] as shown in table 6-11. Comparing the standard design with the manual design in [Taggart 80], we observe that the standard design results in 3% savings in the midship structural area over the manual design. If we assume also that the manual design does not use standard elements, then the cost of the manual design is significantly higher than the cost of the standard design. The two

Zone	tp (cm)	tw (cm)	ww (cm)	tf (cm)	wf (cm)	s (m)
Bottom	2.06	I 2.11	I 39.85	I 3.56	I 40.28	I 1.00
Deck	2.86	I 1.65	I 25.10	I 2.63	I 31.60	I 1.00
Side	1	2.38	I 1.45	I 64.59	I 2.36	I 25.58
Bulkhead	1	1.90	I 1.54	I 57.30	I 2.44	I 32.65

zone	Required Sm (cm ³)	Achieved Sm (cm ³)
Bottom	5892.	I 6319.
Deck	602.	I 2466.
Side	1	3998.
Bulkhead	1	4209.

Required Midship Section Modulus - 62.63 m³
Achieved Midship Section Modulus - 63.45 m³

Midship Structural Area - 7.79 m²

Plate cost - \$ 26426. per m midship section
Tee cost - \$ 41792. per m midship section
Required tee fillet welding - 391 m per m midship section

Table 6-9: Standard Design Characteristics
for VLCC With Tee Spacing = 1 m and
4 Structural Zones

zone	tp (cm)	tw (cm)	ww (cm)	tf (cm)	wf (cm)	s (m)
Bottom	I 2.93	1.21	I 69.07	2.01	I 33.22	I 1.07
Deck	I 3.20	1.53	I 29.77	2.40	I 29.77	I 1.09
Side	1	I 2.25	0.95	I 57.21	1.40	I 43.18
Bulkhead	1	I 1.78	0.97	I 58.29	1.37	I 46.58

zone	Required SM	Achieved SM
Bottom	I 6328.	f 6328.
Deck	654.	2630.
Side	1	4398.
Bulkhead	1	4630.

Required Midship Section Modulus - 62.63 m³
Achieved Midship Section Modulus - 62.63 m³

Midship Structural Area - 7.21 m²

Plate cost - \$ 34420. per m midship section
Tee cost - \$ 64040. per m midship section
Required tee fillet welding - 359 m per m midship section

Table 6-10: Minimum Weight Design Characteristics
for VLCC With 4 Structural Zones

minimum weight designs shown in tables 6-13 and 6-14 have very similar characteristics, although they were started from significantly different initial approximations. Compared to the structural results for the designs with fewer structural zones, the midship structural areas of the standard and the minimum weight designs are reduced as expected. This reduction is small indicating that we reach the point of diminishing returns fast in allowing more variations in the structural elements of the ship midship section. Comparing the results in tables 6-12 and 6-13 we see that the minimum weight design in this case saves 7% of the midship structural area of the standard design. The savings in construction in this case has a present value of \$26,713 per m of midship section, while the present value of the loss of carrying capacity is \$2457 per m of midship section at a freight rate of \$10/mt (\$4914 at a freight rate of \$20/mt). The net benefit of standardization is \$24,256 per m of midship section (\$21,799 in the other case), which is about equivalent to a maximum of \$7.25 million savings for the whole ship if the savings are assumed to continue along the ship length (\$6.5 million at double the freight rate).

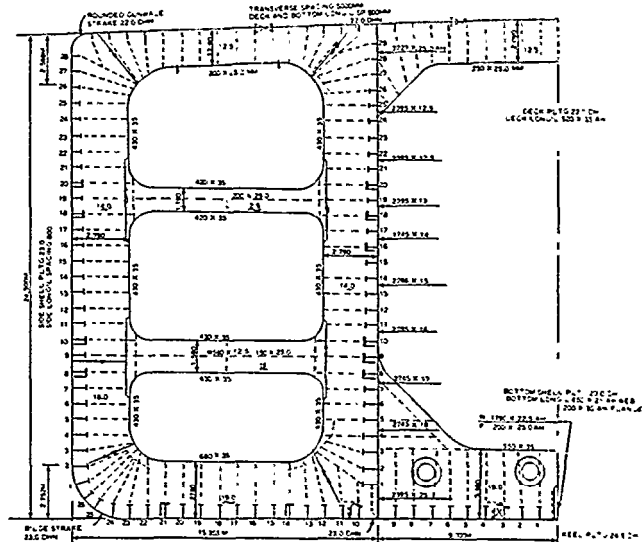


Figure 6-1: Midship Section Manually Designed
Based on ABS [Taggart 80]

Zone		tp (cm)	tw (cm)	I (cm)	t f (cm)	wf (cm)	s (m)
Bottom		2.35	2.10	66.00	3.00	20.00	0.90
Deck		2.30	3.50	53.00		0.	0.90
Side	1	2.30	1.25	74.00	1.60	15.00	0.80
Side	2	2.30	1.15	54.00		15.00	0.80
Side	3	2.30	1.15	44.00	2.50	15.00	0.80
Bulkhead	1	2.50	1.25	79.00	1.60	10.00	0.80
Bulkhead	2	1.60	1.15	54.00		15.00	0.80
Bulkhead	3	1.80	1.15	44.00	1.60	12.50	0.80

Zone		Required (cm ³)	SM I	Achieved (cm ³)	SM
Bottom	I	5303.		6258.	
Deck	i	542.	i	2880.	
Side	1	3199.	I	3734.	
Side		1973.		2977.	
Side	3	747.	I	1740.	
Bulkhead	1	3367.		3551.	
Bulkhead	2	2077.	I	2879.	
Bulkhead	3	186.		1533.	

Required Midship Section Modulus - 62.63 m³
Achieved Midship Section Modulus - 62.74 m³

Midship Structural Area - 7.61 m²

Place cost - \$ 30895. per m midship section
Tee Cost - \$ 89984. per m midship section
Required tee fillet welding - 461 m per m midship section

**Table 6-11: Manual Design Characteristics
for VLCC with 8 Structural Zones -
Approximation of Figure 6- 1**

ZONE		tp (cm)	tw (cm)	ww (cm)	tf (cm)	wf (cm)	s Cm)
Bottom		2.68	1.21	70.18	2.02	33.29	1.10
Deck		3.12	1.40	31.59	2.33	31.59	0.75
Side	1	2.25	0.97	58.26	1.52	38.48	1.10
Side	2	2.25	0.81	48.38	1.27	34.20	1.10
Side	3	2.25	0.80	41.09	0.80	17.37	1.10
Bulkhead	1	1.78	0.97	58.41	1.51	42.03	1.10
Bulkhead	2	1.43	0.81	48.65	1.25	38.00	1.10
Bulkhead	3	0.91	0.80	42.93	0.80	19.02	1.10

zone		Required (cm ³)	SM I	Achieved (cm ³)	SM
Bottom	I	6481.		6480.	
Deck	I	452.		2801.	
Side		4398.		4392.	
Side	2	2713.		2711.	
Side	3	1027.		1027.	
Bulkhead	1	4630.		4628.	
Bulkhead	2	2855.		2855.	
Bulkhead	3	1081.		1081.	

Required Midship Section Modulus - 62.63 m³
Achieved Midship Section Modulus - 62.62 m³

Midship Structural Area - 6.89 m²

Plate Cost - \$ 32721. per m midship section
Tee cost - \$ 62437. per m midship section
Required tee fillet welding - 397 m per m midship section

**Table 6-13: First Minimum Weight Design
Characteristics for VLCC With 8 Structural
Zones - Initial Approximation from
Standard Design**

zone		tp (cm)	tw (cm)	ww (cm)	tf (cm)	Wf (cm)	s (m)
Bottom		2.06	1.59	86.28	2.39	30.42	1.00
Deck		2.86	1.83	50.19	2.92	31.77	1.00
Side	1	2.38	1.45	64.59	2.36	25.58	1.00
Side	2	2.38	1.31	57.30	2.22	23.02	1.00
Side	3	2.38	1.09	28.65	1.50	17.88	1.00
Bulkhead	1	1.90	1.54	57.30	2.44	32.65	1.00
Bulkhead	2	1.43	1.40	50.19	2.22	31.34	1.00
Bulkhead	3	1.27	1.09	28.65	1.50	17.88	1.00

zone		Required (cm ³)	SM I	Achieved (cm ³)	SM
Bottom		5892.		9160.	
Deck		602.		5925.	
Side		3998.		5559.	
Side	2	2466.		4166.	
Side	3	934.		1081.	
Bulkhead	1	4209.		5783.	
Bulkhead	2	2596.		4294.	
Bulkhead	3	983.		1028.	

Required Midship Section Modulus - 62.63 m³
Achieved Midship Section Modulus - 63.16 m³

Midship Structural Area - 7.39 m²

Plate cost - \$ 25420. per m midship section
Tee cost - \$ 43055. per m midship section
Required tee fillet welding - 391 m per m midship section

**Table 6-12: Standard Design Characteristics
for VLCC With Tee Spacing = 1 m and
8 Structural Zones**

ZONE		tp (cm)	tw (cm)	ww (cm)	tf (cm)	wf (cm)	s (m)
Bottom		2.60	1.41	48.54	2.35	48.54	1.10
Deck		3.20	2.10	26.99	2.23	26.99	0.79
Side	1	2.25	0.99	59.31	0.96	57.57	1.10
Side	2	2.25	0.81	48.64	0.95	45.29	1.10
Side	3	2.25	0.80	41.58	0.80	16.86	1.10
Bulkhead	1	1.78	1.04	62.23	0.94	58.21	1.10
Bulkhead	2	1.43	0.84	50.66	1.01	44.05	1.10
Bulkhead	3	0.91	0.80	43.38	0.80	18.55	1.10

ZONE		Required (cm ³)	SM I	Achieved (cm ³)	SM
Bottom		6481.		6470.	
Deck		474.		2149.	
Side		4398.		4321.	
Side	1	2713.		2712.	
Side	3	1027.		1027.	
Bulkhead	1	4630.		4537.	
Bulkhead	2	2855.		2855.	
Bulkhead	3	1081.		1081.	

Required Midship Section Modulus - 62.63 m³
Achieved Midship Section Modulus - 62.57 m³

Midship Structural Area - 6.88 m²

Plate cost - \$ 32131. per m midship section
Tee cost - \$ 64324. per m midship section
Required tee fillet welding - 391 m per m midship section

**Table 6-14: Second Minimum Weight Design
Characteristics for VLCC With 8 Structural
Zones - Initial Approximation from
Manual Design**

7. Conclusion

As was seen from the examples presented in the previous section, the heuristic algorithm developed for automating the use of standardization in ship structural design leads to substantial savings in the costs required to build the structure of a ship at only a small expense in the loss of cargo carrying capacity of a slightly heavier ship. Both automated methodologies are certainly superior to the manual process of ship structural design as was seen in the second example using the design from [Taggart 80].

The standardization methodology could be easily expanded to treat alternate ship designs and also to treat double bottoms, transverse structural elements and other parts of the ship and not just the midship section. It is evident from our analysis, that it is worthwhile for ship designers to consider the costs of the structural materials used in the design of a ship, since wise selection of standard elements which are manufactured cheaply can lead to significant savings in the material structural cost of a ship.

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